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(54) Liquid crystal display

(57) A non-polarising, Bragg-reflecting liquid crystal display is provided including a first (13) and second (14,28) substrate, and liquid crystal material (40) located between the first substrate (13) and the second substrate (14, 28). A fiber-optic faceplate (50) may function as a first substrate. Alternatively, a fiber-optic faceplate (50) may be located on the side of the first substrate (13) opposite from the liquid crystal layer (40). The fiber-optic faceplate (50) may include optical fibers that extend between a front face and a rear face and fiber cladding materials located between the optical fibers. The fiber cladding material may be further opaquely masked on the front face.

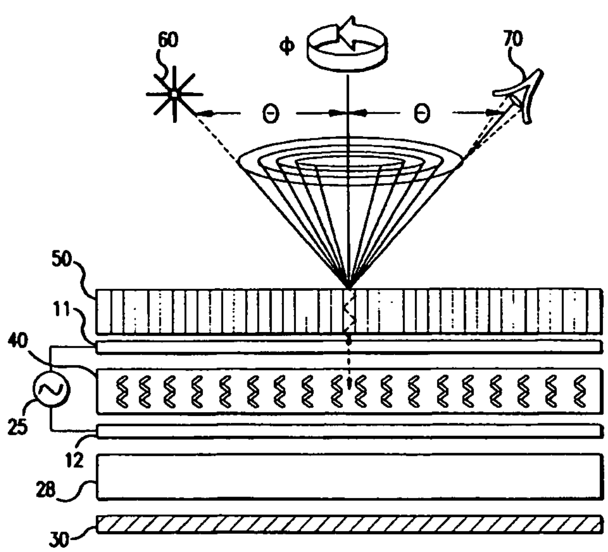

FIG.6a

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Description

Bragg-reflecting displays are well known in the art. Figures 1-5 show s veral types of conventional Bragg-reflecting liquid crystal displays (LCDs). For example, Figure 1 shows a display that uses cholesteric LC materials, Figure 2 shows a display that uses liquid crystals with polymer stabilized cholesteric textures (PSCT), Figure 3 shows a display that uses liquid crystals with surface stabilized cholesteric textures (SSCT), Figure 4 shows a display that uses polymer dispersed cholesteric liquid crystal (PDCLC) and Figure 5 shows a display that uses holographically formed polymer dispersed liquid crystal (H-PDLC). A brief description of each of these five types of displays is provided below.

Figure 1a shows a first substrate 10, a second substrate 20 and cholesteric liquid crystal materials located between the first and second substrates. In the off-state, a single domain reflects light with the approximate wavelength, $\lambda = nP$, that satisfies the Bragg condition, where n is the average index of fraction and P is the pitch length associated with the chiral liquid crystal. The pitch length governs the selective wavelength or color to be reflected. All other wavelengths of light are transmitted. The off-state configuration of the LC is referred to as the planar texture as shown in Figure 1a. As shown in Figure 1b, upon application of an electric field by a voltage source 25, the pitch axes form an intermediate disorganized state known as the focal conic texture. This state is weakly scattering and the background (usually black) is easily visible. The focal conic state is metastable and may remain for hours before relaxing back to the planar texture (Figure 1a). As shown in Figure 1c, when a larger electric field is applied, all the cholesteric LC molecules align parallel to the field (for an LC material with positive dielectric anisotropy, $+\Delta\varepsilon$) and the display is transparent so that the background is observed. This is therefore a monochrome display that typically operates between a reflected color λ and the color of the background which is usually a black absorber (not shown). The angular dependency of the display is strongly dictated by the Bragg condition, $\lambda = nP \cos \theta$, where θ is the angle between an observer and the normal to the substrate 10. Therefore, as the source of illumination and observer move off axis, the peak reflection shifts to shorter wavelengths.

The PSCT display shown in Figure 2 operates in a similar manner to the display shown in Figure 1, except a small amount of polymer forming network is added to stabilize the focal conic state indefinitely. As shown in Figure 2a, the display operates according the Bragg condition, $\lambda = nP$, in the off state. When a low electric field is applied as shown in Figure 2b, the focal conic texture forms. However, the polymer network stabilizes the focal conic texture so that the electric field can be turned off and the focal conic texture remains indefinitely. Upon application of a larger electric field as shown in Figure 2c, a completely aligned texture arises (for LC materials with positive dielectric anisotropy, $+\Delta\varepsilon$).

After the field is removed, th configuration r laxes back to the planar texture in Figure 2b. This display is typically operated b tween the planar t xture (Figur 2a) and the focal conic textur (Figure 2b) for color monochrome operation and bistable memory operation. The angular dependence of the display is also strongly dictated by the Bragg condition, $\lambda = nP \cos \theta$, where θ is the angle between the observer and the normal to the substrate 10.

The SSCT display shown in Figure 3 operates under the same principles as the PSCT display except a random-type surface alignment is used instead of the polymer network. Figure 3a shows the planar texture, Figure 3b shows the focal conic texture and Figure 3c shows the aligned texture. The random-type, non-rubbed surface alignment gives added stability to the focal conic texture (Figure 3b) for bistable memory operation.

The PDCLC display shown in Figure 4 also utilizes Bragg-reflection in a manner similar to that in Figures 1-3, except the LC configuration is different. The PDCLC employs droplets of cholesteric LC material dispersed in an isotropic polymer. The cholesteric LC material is of the negative dielectric type ($-\Delta\varepsilon$). In the off state shown in Figure 4a, the stable concentric director configuration is nearly transparent. As shown in Figure 4b, upon application of an electric field, the cholesteric LC molecules align perpendicular to the field direction because of their $-\Delta\varepsilon$ and form the planar texture within the droplets. Therefore, the display is reflecting in the field-on state. After the field is removed, the planar texture (Figure 4b) reverts back to the concentric texture (Figure 4a). The angular dependence of the display is also strongly dictated by the Bragg condition, $\lambda = nP \cos \theta$.

The H-PDLC display shown in Figure 5a uses optical interference techniques to phase separate the droplets of nematic LC and polymer into separate and distinct planes. This sets up a modulation in droplet densities, regions of droplets and regions of polymer. The resulting optical interference of this refractive index modulation is strongly dictated by the Braggs condition. The angular dependence of the display is also strongly dictated by the Bragg condition, $\lambda = nP \cos \theta$. The H-PDLC display is advantageous because it can ideally reflect 100% of the incident illumination at the Bragg wavelength resulting in a brighter color display compared to those shown in Figures 1-4. As shown in Figure 5b, upon application of an electric field, the refractive index modulation disappears if the ordinary index of refraction of the LC (n_o) matches that of the polymer (n_p) and all light is transmitted. After the electric field is turned off, the display relaxes back to the reflecting state shown in Figure 5a.

Fiber-optic faceplates (FOFPs) are known in the art. Reflective twisted nematic (TN) LCDs that utilize polarizers and FOFPs are also known. The polarizers polarize the light passing through the LC cell. However, these

displays are not Bragg-reflecting displays. Rather, incident illumination is polarized on input and passes through the entire LC cell and strikes a specular reflector that sends th light ray back through the LC cell, through at least one polarizer, used to analyze the polarization state exiting the LC cell, and out through the FOFP. The FOFP functions to expand the viewing angle and minimize the pixel "shadowing" of these traditional reflective twisted nematic LCDs.

Direct-view transmissive color LCDs that utilize FOFPs are known. These direct view transmissive LCDs also utilize polarizers. The FOFP also acts as a front containing element adjacent to the LC layer. The FOFP provides azimuthal averaging of off-axis light. The azimuthal averaging properties of the FOFP result in symmetrical viewing cones, effectively averaging out the typical LCD anisotropy.

The front FOFP of a direct view display may include an array of individual optical fibers that are fused together with an interstitial cladding material and then cut and polished to a desired thickness to form a plate. The creation of FOFPs with varying optical characteristics is well known in the art. The optical fibers are designed to transmit through total internal reflection light incident at controlled input or acceptance angles while rejecting or absorbing light incident at larger angles.

Prior applications of FOFPs on both reflective and transmissive LCDs have utilized twisted nematic LCDs, which rely on the principles of light polarization and polarization analysis for their operation. This makes their integration with FOFPs difficult and relatively inefficient since FOFPs do not preserve light polarization during internal reflection.

The present invention provides a non-polarizing, Bragg-reflecting LCD having a FOFP that reflects light in a symmetric output cone. The FOFP serves as the top substrate of the display to enhance light collection efficiency and viewing angle performance. The FOFP improves the overall off-specular viewing performance of the display by averaging azimuthal and declination angle components of both incident and reflected light. Monochrome reflective displays that operate on Bragg's principal are severely limited in viewing angle because of the wavelength shift and luminance decay that occurs off the plane of incidence to the display. The FOFP stabilizes the chromaticity and effective reflected luminance for larger viewing angles. In addition, the FOFP may eliminate noticeable inhomogenities in reflective mode displays.

For purposes of the present invention, the term FOFP is interpreted in its broadest sense as any material which embodies the essential optical properties of a FOFP. Thus, the functioning of the present invention is not dependent upon the use of a fused plate of optical fibers but rather on any material layer, including a fused plate of optical fibers, which is capable of total internal reflection and rotational azimuthal and declination angle averaging. It should be apparent to those skilled in the art that these essential optical properties may b imparted to a range of mat rials, thus producing FOFP optical equivalents. These could include micro-machined or preformed glass or plastic substrates with a plurality of optical features, a variety of polymer networks containing a duality of materials with differing refractive indices or birefringence produced by physical alignment or stress, or any other approach able to result in a substrate containing a plurality of cylindrical features whose boundaries are defined by a discontinuity of refractive indices.

Other objects, advantages and salient features of the invention will become apparent from the following detailed description taken in conjunction with the annexed drawings, which disclose preferred embodiments of the invention.

The invention will be described with reference to the following drawings in which like reference numerals refer to like elements and wherein:

Figures 1a-1c show a cholesteric reflecting display;
Figures 2a-2c show a polymer stabilized cholesteric texture display;
Figures 3a-3c show a surface stabilized cholesteric texture display;
Figures 4a-4c show a polymer dispersed cholesteric liquid crystal display;
Figures 5a-5c show a holographically formed polymer dispersed liquid crystal display;
Figures 6a-6b show liquid crystal displays of the present invention;
Figure 7 is one embodiment of the FOFP of the present invention;
Figure 8 is another embodiment of the FOFP of the present invention; and
Figures 9a-9b show other embodiments of the liquid crystal display according to the present invention.

The present invention enhances the viewing performance of refracted LCDs that operate on Bragg's principle. Unlike the prior art LCDs, the present invention does not require polarizers, which makes integration with the FOFP much simpler and more efficient.

Figures 1-5 show existing LCDs that operate on the Bragg principle and the range of LC configurations that correspond with the present invention. In other words, the LC material of the present invention may include cholesteric liquid crystals, polymer stabilized cholesteric textures, surface stabilized cholesteric textures, polymer-dispersed cholesteric liquid crystals and holographically formed polymer dispersed liquid crystals.

As shown in Figure 6a, the present invention includes a FOFP 50 that functions as the top substrate or containing element of the display. Alternatively, the FOFP 50 may be on the front substrate as shown in Figure 6b. The FOFP 50 enhances the effective viewing angle on reflectance and also minimizes the undesirable appearanc of inhomogenities in the display.

The most dominant effect of the FOFP 50 is the increased reflectanc at non-specular viewing angles. In operation of the Bragg-reflecting, non-polarizing display, the optimal display image reflectance occurs at the specular angle, wher both incident illumination and the observer lie in the same plane. In prior art displays, additional unwanted specular reflections from the front surface and other internal optical layers makes the reliance on a specular observation angle very undesirable. However, the FOFP 50 actually collects light at all angles within the conical region, including the specular angle, and provides an averaged reflected output over all azimuthal and declination angles thereby enhancing the reflectance and enabling effective non-specular viewing directions.

In addition to the FOFP 50 in Figure 6a, the display may also include ITO electrodes 11, 12 and LC material 40 interposed between the ITO electrodes 11, 12. A substrate 28 such as glass may also be provided. A voltage source 25 may be connected between the electrodes 11, 12 to provide a varying voltage. A black absorber 30 may be provided on the bottom of the LCD to absorb non-reflected light. As discussed above, the LC material 40 may include any one of cholesteric liquid crystals, polymer stabilized cholesteric textures, surface stabilized cholesteric textures, polymer-dispersed cholesteric liquid crystals and holographically formed polymer dispersed liquid crystals. The LC material 40 may also include any other type of Bragg-reflecting LC material that is selectively reflective of a desired wavelength of light.

In Fig. 6b, first and second substrates 13 and 14 are provided each having ITO electrodes. The FOFP 50 is then provided on the front side of the first substrate 13.

Light from illumination source 60 is incident on the FOFP 50 at an angle θ with respect to a normal to the plane of the FOFP 50. The light from source 60 is averaged over azimuth, Φ, and declination, θ , by the FOFP 50. The light is then reflected from LC material 40 and re-enters the FOFP 50. The light is again averaged over azimuth and declination by FOFP 50. The light that enters the observer's eye 70 has therefore been averaged over azimuth and declination twice and provides effective and symmetric viewing characteristics at all viewing positions. Effective reflectance of the display is no longer restricted to the specular angle. The image from the display is much more homogeneous in color and luminance over viewing angle than the same display image without the FOFP 50.

Figure 7 shows one embodiment of a FOFP 50 having optical fibers 52 and transparent cladding material 54. Figure 8 shows another embodiment of a FOFP 50 with the surface masked with opaque cladding apertures 56. This may be accomplished by coating the FOFP 50 with a blocking layer that covers only the cladding apertures of the FOFP 50. This coating can be, for example, a metalmetal oxide anti-reflectiv coating applied over the FOFP 50 and then pattern away over the fiber openings while maintaining the opaque coating on the cladding apertures. Th anti-reflectiv natur of the coating reduces ambient reflections from the FOFP 50. This blocks the diffracted light in th dark-stat from highluminance off-axis directions from coupling into th on-axis direction which greatly improves the on-axis and overall contrast ratio. Other coating methods are also within the scope of this invention. For example, the fiber cores and the cladding materials may be made from chemically different materials. The FOFP can then be treated with gas to turn the cladding opaque.

Figure 9a also shows a Bragg-reflecting non-polarizing LC display according to the present invention. Three separate LC cells 90, 92 and 94 are provided within the display apparatus. The first cell 90 includes first substrate 10 and second substrate 10a. The LC material 42 is located between the first and second substrates 10, 10a and is reflective of a desired wavelength of light. The second LC cell 92 includes third substrate 10b and fourth substrate 10c located on opposite sides of the LC material 44 that is reflective of a wavelength of light different than the wavelength corresponding to the LC material 92 of the first cell 90. The third cell 94 includes fifth substrate 10d and sixth substrate 20 located on opposite sides of the LC material 46 that is reflective of a wavelength of light different than the wavelength corresponding to the LC material 42 and 44 of the first cell 90 and the second cell 92. As is understandable to one skilled in the art, each of the cells reflects a different wavelength of light. The FOFP 50 is located on the side of the first substrate 10 opposite from the LC material 42. Voltage sources (not shown in Figure 9) alter the LC material 42, 44 and 46 and thereby reflect the selective wavelengths as is apparent to one skilled in the art. Intermediate substrates 10a, 10b, 10c and 10d may be reduced or eliminated to eliminate parallax effects. Furthermore, FOFP 50 may function as the top substrate or containing element of the display as in Figure 6a.

Figure 9b shows a further non-polarizing Bragg-reflecting display in which FOFPs 50a and 50b are provided between each of the respective LC cells 90, 92 and 94. Although not shown, ITO electrodes are also provided as in other embodiments.

The FOFP 50 is utilized with any type of non-polarizing Bragg-reflecting display such as described above. Other Bragg-reflecting displays can also use the FOFP 50 of the present invention. This provides several important advantages. First, there is an enhanced reflected luminance at non-specular angles. Second, angular chromaticity shifts resulting from anisotropies in LC configurations and illuminant spectral power distributions are minimized or eliminated. Third, the FOFP minimizes observed inhomogeneities in display texture. As shown in Figures 6a and 6b, the incident light is funneled through the FOFP 50, and impinges on the reflecting LC material 40. The light reflected from the material 40 is then transferred back out the FOFP 50 to the observer's eye 70. The light that is incident on the cell is azimuthally

averaged before the LC cell and the light reflected by the LC material 40 is again averaged via a second pass through the FOFP 50.

For Bragg-reflecting LC cells, th highest reflection efficiency is obtained at the specular angle. How v r, this viewing direction is poor in prior art devices because the ambient light is also spectrally reflected off the top substrate and other internal optical layers. The FOFP 50 collects light from all incident angles and azimuthally averages it over angle ϕ and declination angle θ thereby enhancing reflectance at all non-specular viewing directions. FOFPs also minimize wavelength shifts at wide viewing angles making the shift in color not as noticeable. Also, any inhomogeneities in the display texture are removed by the azimuthal averaging effect of the FOFP 50.

Claims

1. A non-polarizing, Bragg-reflecting liquid crystal display comprising:

   a fiber-optic faceplate located on a front side of the display;
   a first substrate; and
   liquid crystal material located between the first substrate and the fiber-optic faceplate.

2. A liquid crystal display comprising:

   first and second substrates;
   first liquid crystal material located between the first and second substrates;
   a third substrate;
   second liquid crystal material located between the second and third substrates;
   a fourth substrate; and
   third liquid crystal material located between the third and fourth substrates, wherein the first, second and third liquid crystal materials reflect light of first, second and third wavelengths, respectively, wherein the first substrate is located on a front side of the display and includes a fiber-optic faceplate.

3. A liquid crystal display comprising:

   liquid crystal material selectively reflective of a desired wavelength of light; and
   a fiber-optic faceplate located on the liquid crystal material.

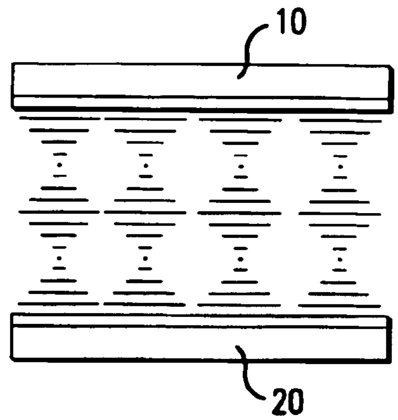

FIG.1a

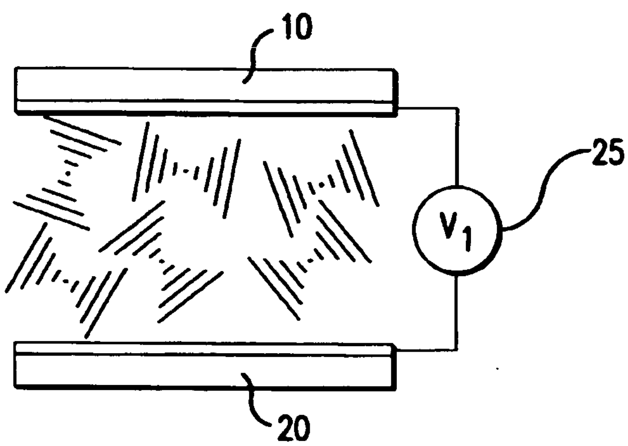

FIG.1b

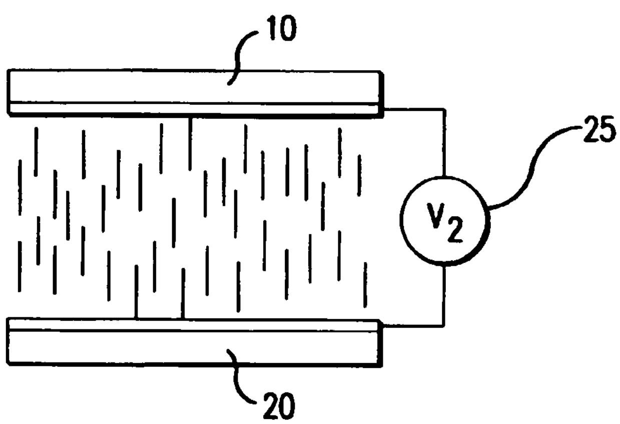

FIG.1c

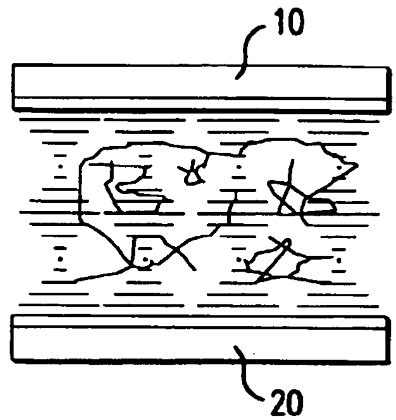

FIG.2a

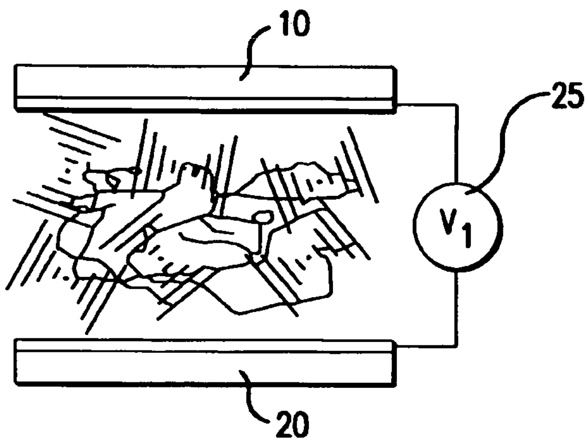

FIG.2b

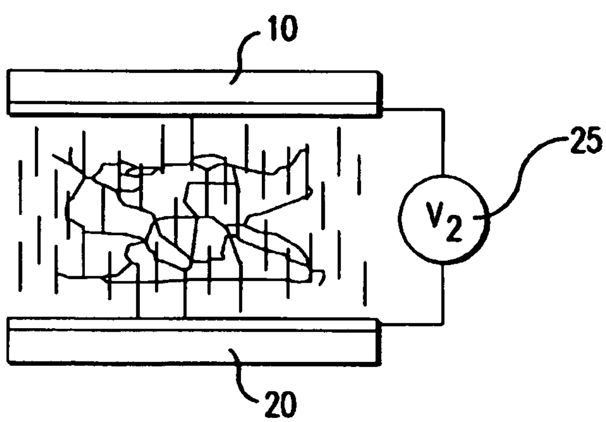

FIG.2c

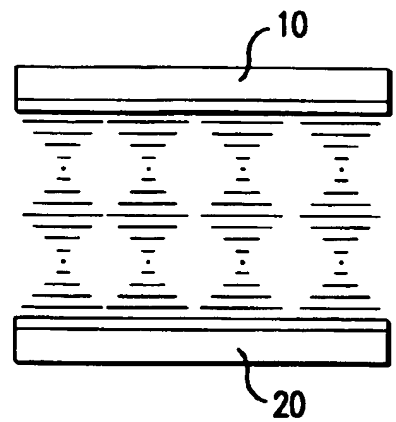

FIG.3a

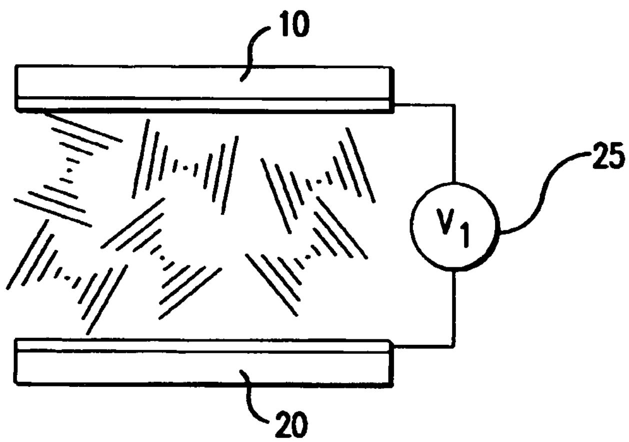

FIG.3b

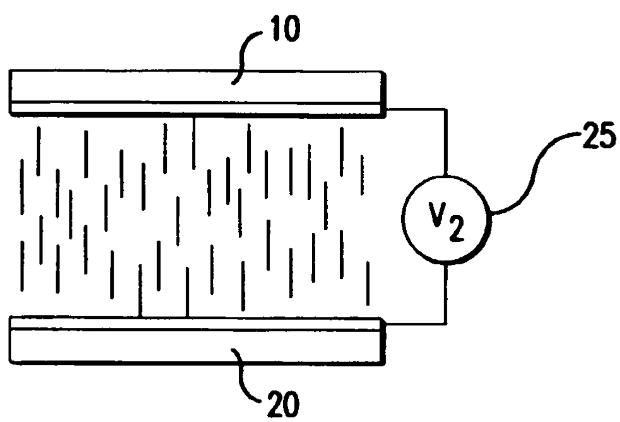

FIG.3c

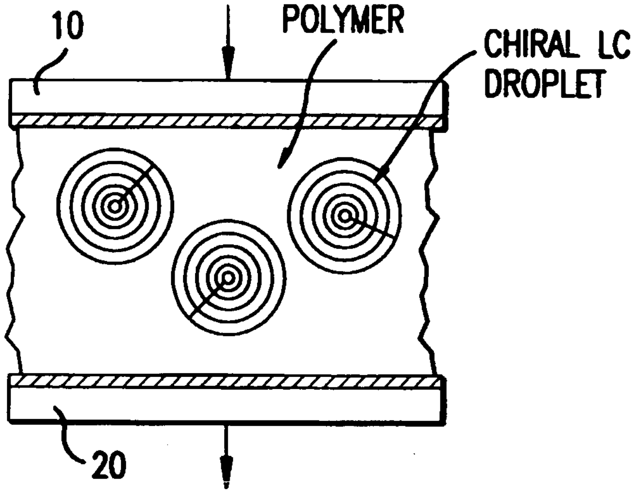

FIG.4a

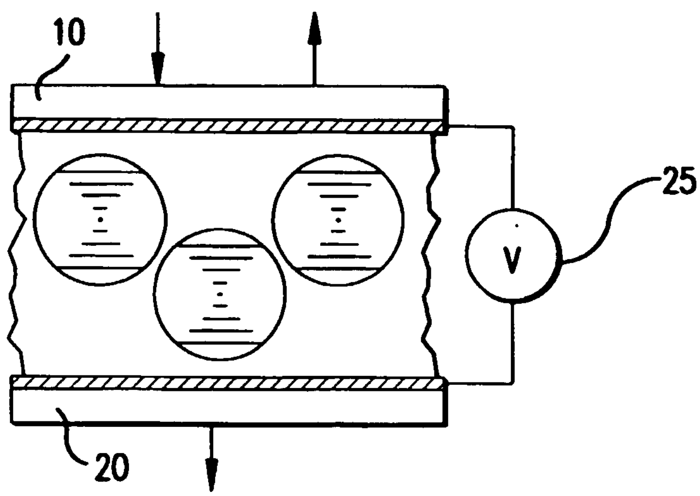

FIG.4b

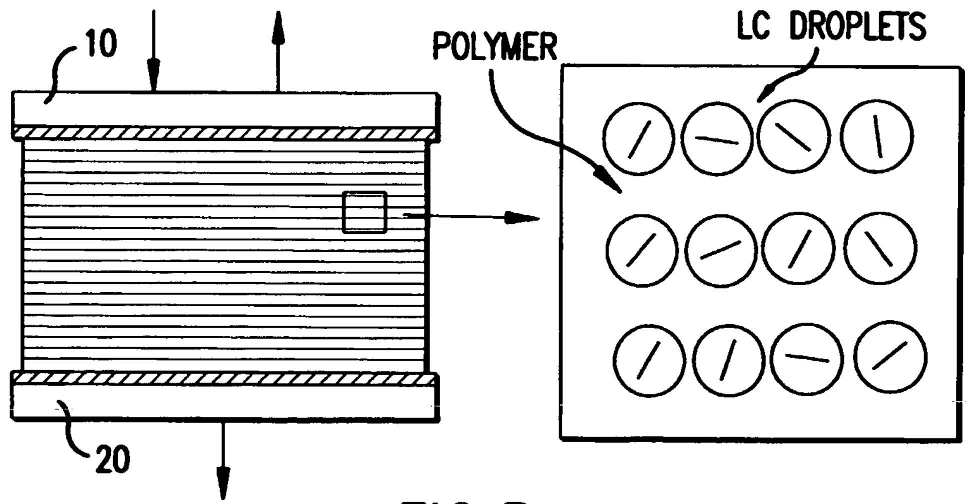

FIG.5a

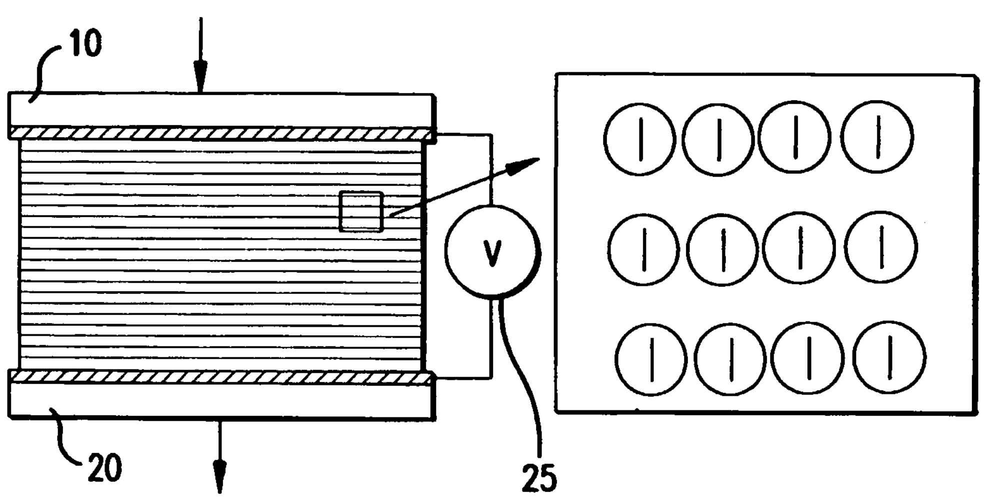

FIG.5b

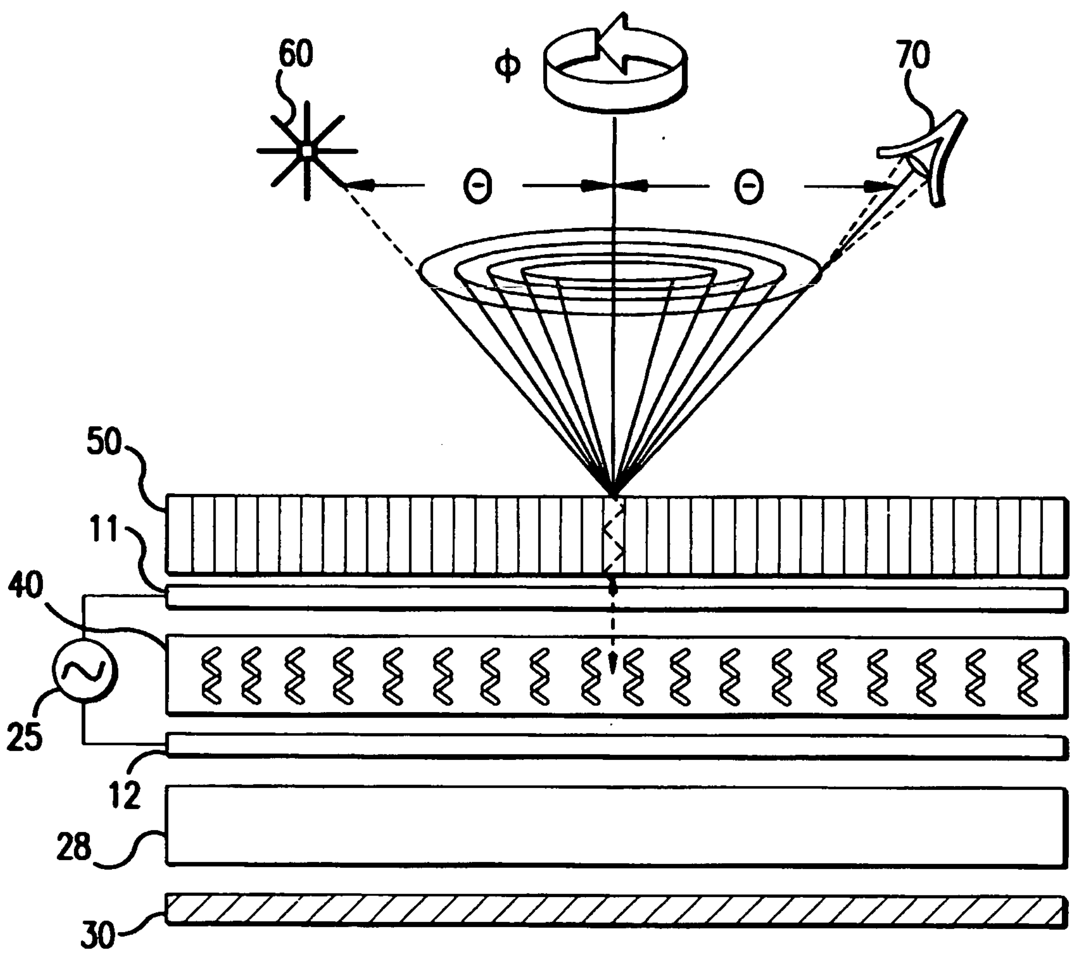

FIG.6a

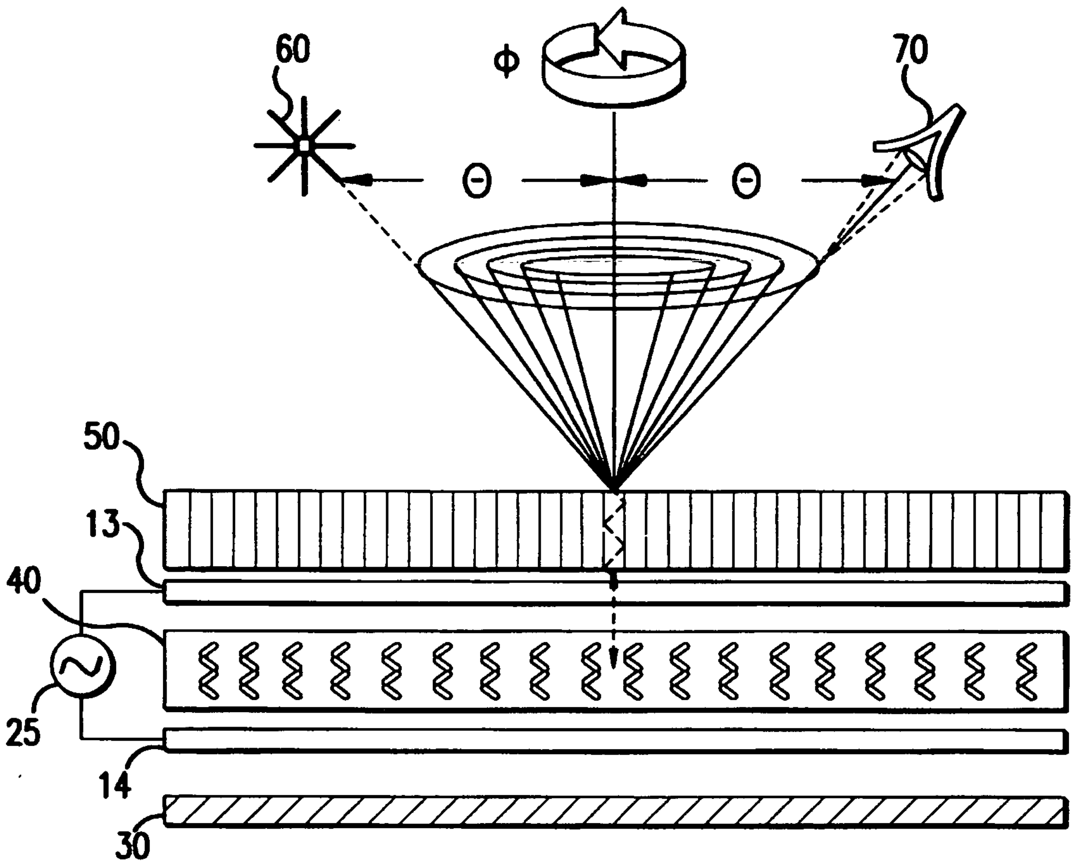

FIG.6b

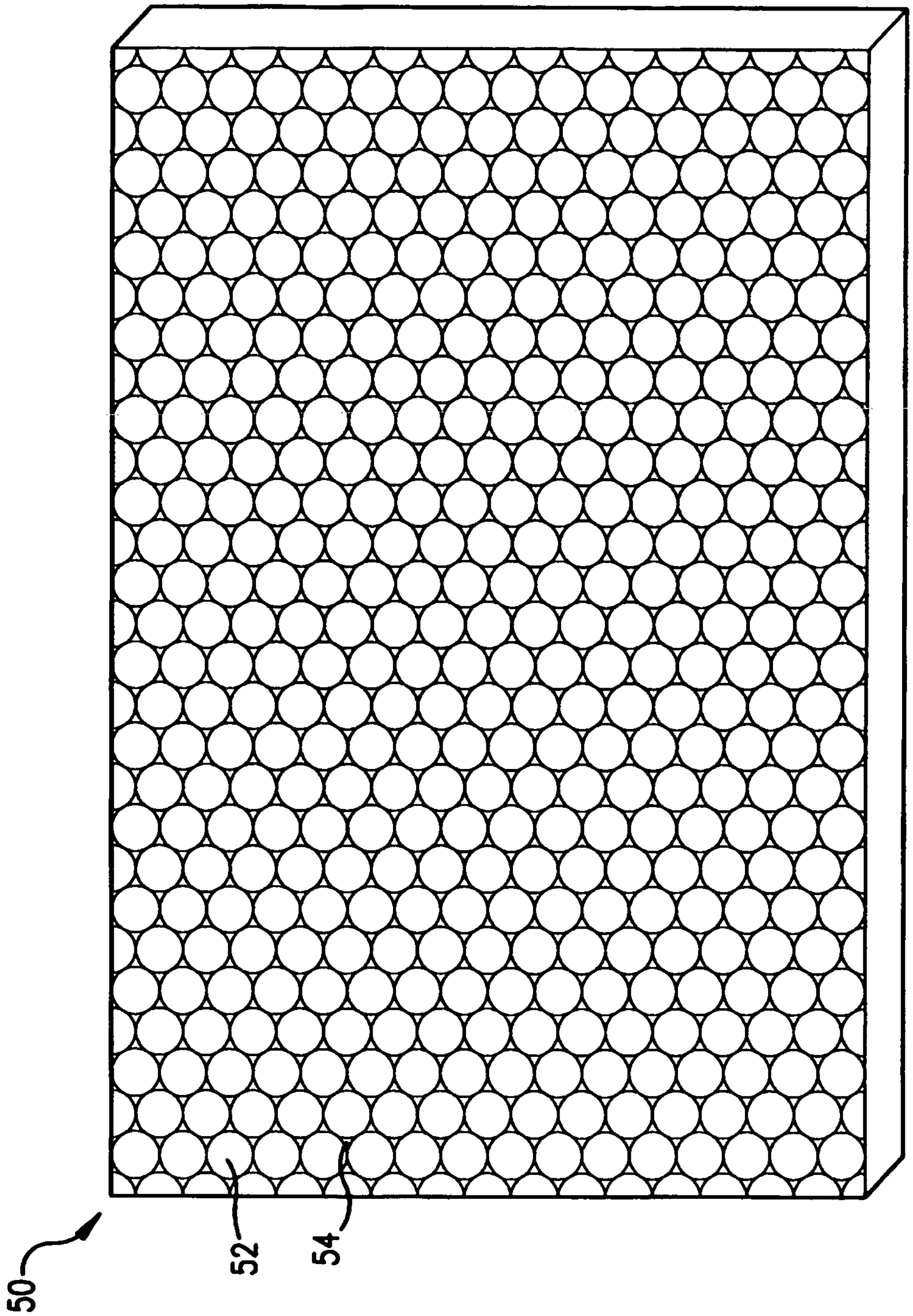

FIG.7

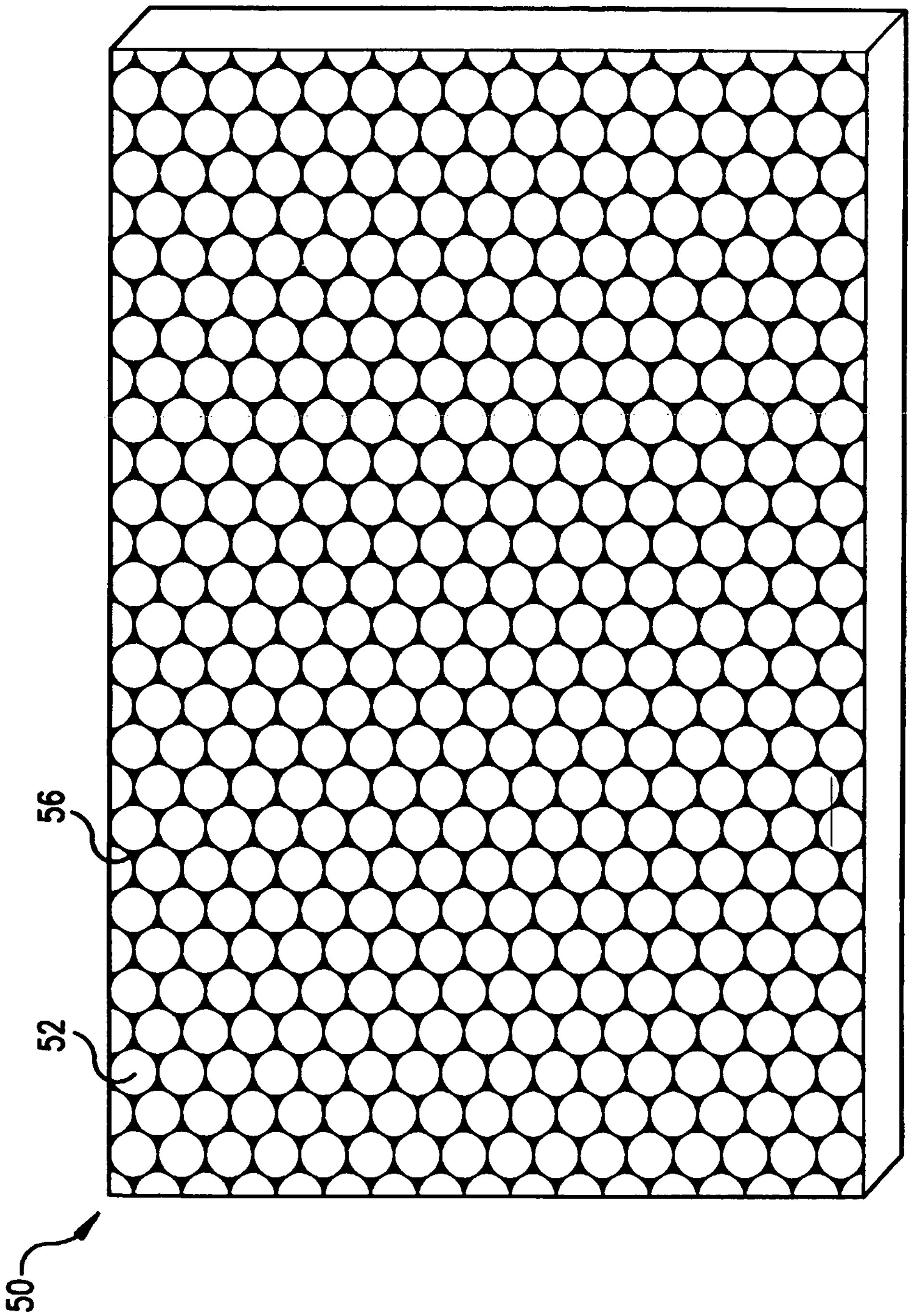

FIG.8

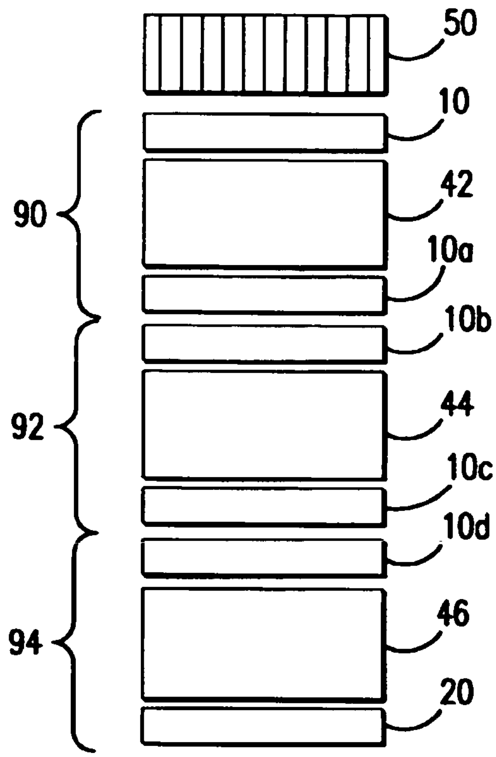

FIG.9a

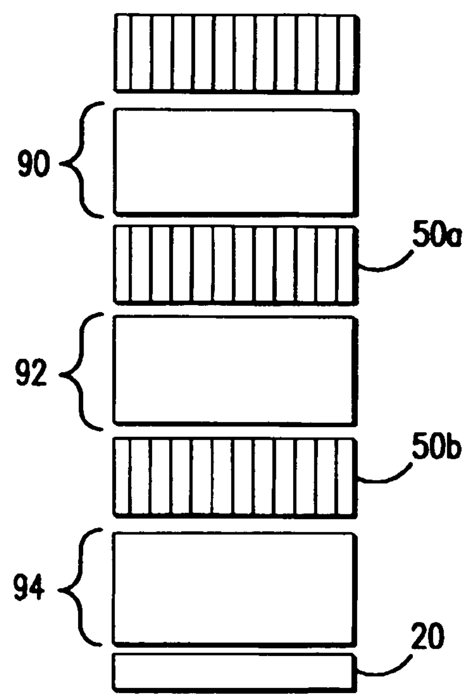

FIG.9b

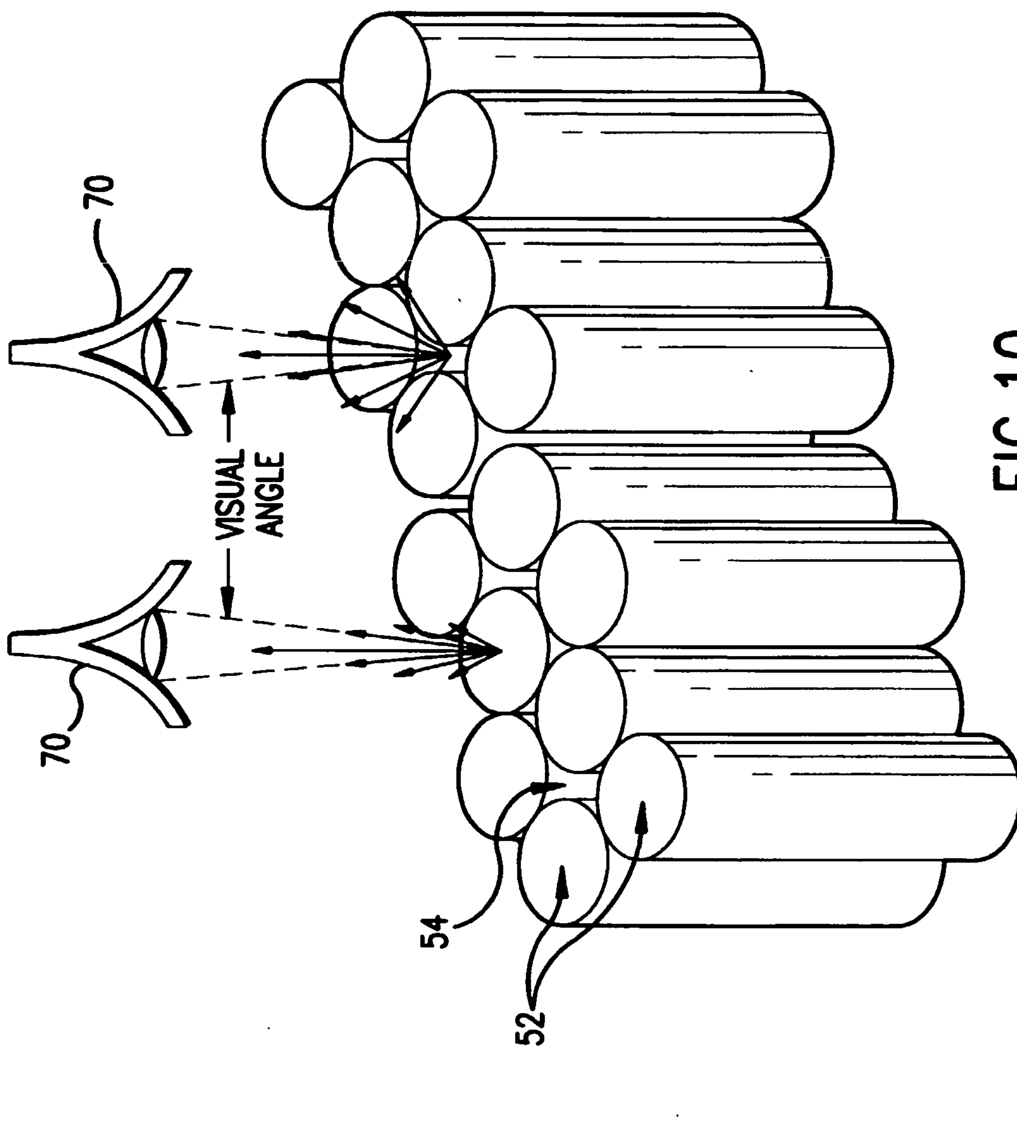

FIG.10

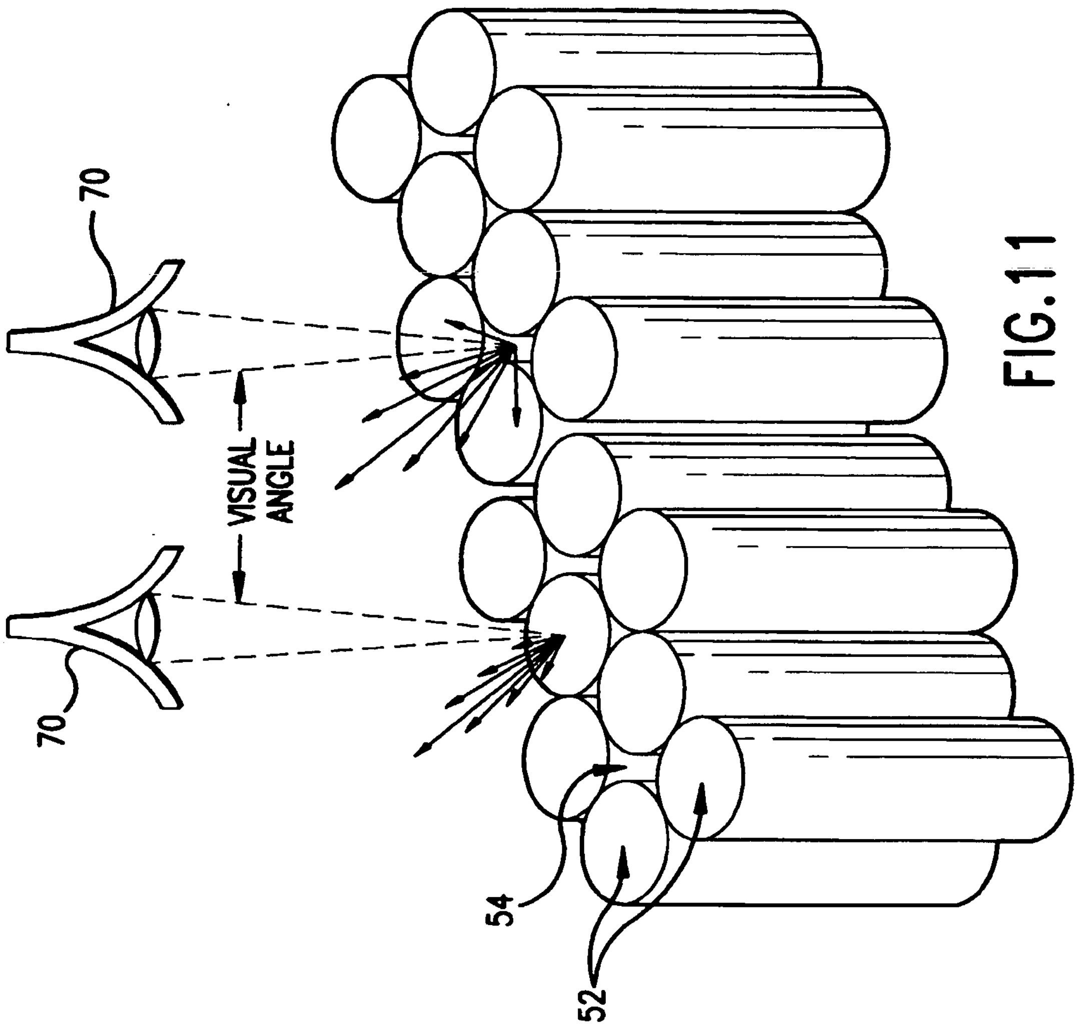

FIG. 11